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Enhancements to the Shaft Modeling Tool Kit

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for

Transportation Development Centre
Policy and Coordination Group
Transport Canada

and

Power Transmission System, Section DMEE 2-7
Department of National Defence

November 1990

472103

DDN 461691

The contents of this report reflect the views of Fleet Technology Limited and not necessarily the official view or opinions of the Transportation Development Centre of Transport Canada or the Department of National Defence.

Un sommaire en français de ce document est inclus avant la table des matières.

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ACKNOWLEDGEMENTS

This project was conducted under the auspices of the Transportation Development Centre (TDC), Policy and Coordination Group, Transport Canada, and the Power Transmission Section DMEE-2-7 of the Department of National Defence (DND). The TDC Project Officer for this work was Mr. Pierre Sémery and the authors wish to acknowledge Mr. Sémery's contribution in helping to define the project and in providing very valuable scientific direction to the program. The DND Project Officers were LCdr Greg Cottingham, LCdr Bob Dunlop, and Steven Bobyn, whose input and ideas were very appreciated and contributed significantly to the development of the final version of the program.

Transport Canada / Transports Canada

PUBLICATION DATA FORM

1. Transport Canada Publication No.	2. Project No.	3. Recipient's Catalogue No.
TP 10766E	7459	

4. Title and Subtitle

Enhancements to the Shaft Modeling Tool Kit

5. Publication Date
November 1990

6. Performing Organization Document No.
C93636C

7. Author(s)
D.N. Bruce Cowper, Ron Ritch, and Mike Steele

8. Transport Canada File No.
1460-286

9. Performing Organization Name and Address
Fleet Technology Limited
16, 6325 11th Street S.E.
Calgary, Alberta
T2H 2L6

10. DSS File No.
XSD89-00185-(631) / A

11. DSS or Transport Canada Contract No.
—

12. Sponsoring Agency Name and Address
Transportation Development Centre (TDC)
Guy Favreau Complex
200 René Lévesque Blvd. West
West Tower, Suite 601
Montreal, Quebec H2Z 1X4

13. Type of Publication and Period Covered
Final (March 90/Nov. 90)

14. Project Officer
P. Sémery

15. Supplementary Notes (Funding programs, titles of related publications, etc.)

Partly funded by the Canadian Coast Guard.

16. Abstract

The Shaft Modeling Tool Kit Version 1.0 was the first available comprehensive software package for the analysis of ice class shafting and propeller systems. Since its first issue in October 1988, the program has been used to study not only the dynamic problems associated with ice class shaftlines, but also the vibrational and alignment problems of open waters vessel shaftlines. Enhancements to version 1.0 focused on modifying the database section of the program, adding the capability to specify a bi-linear stiffness for each bearing, adding the capability to specify an input force at any location along the shaftline, and modifying the regulations section of the program to allow for the analysis of a number of regulations. These enhancements and others were designed and implemented into version 2.0 of the program. The software was tested against analytical calculations after the code was developed. In addition, several propeller ice torque time histories were produced by comparing the response predictions of the program with measured full scale shaft torque data. The results are presented in the form of time history plots.

The suite of programs in version 2.0 provide the user with the capability to: access significant full scale data, display Lloyd's, ABS, Bureau Veritas, NES 304 (Defence Department only), and CASPPR Regulations for Powering, Shafting, and Propellers, and model a generalized shaftline to calculate the torsional, axial, and transverse (whirling) vibration characteristics, as well as the static alignment condition.

17. Key Words	18. Distribution Statement
Shafting, propellers, modeling	Limited number of copies available from the Transportation Development Centre

19. Security Classification (of this publication)	20. Security Classification (of this page)	21. Declassification (date)	22. No. of Pages	23. Price
Unclassified	Unclassified	—	42	—

Transports Canada Transport Canada

FORMULE DE DONNÉES POUR PUBLICATION

1. N° de la publication de Transports Canada	2. N° de l'étude	3. N° de catalogue du destinataire
TP 10766E	7459	

4. Titre et sous-titre

Enhancements to the Shaft Modeling Tool Kit

5. Date de la publication
Novembre 1990

6. N° du document de l'organisme exécutant
C93636C

7. Auteur(s)
D.N. Bruce Cowper, Ron Ritch et Mike Steele

8. N° de dossier — Transports Canada
1460-286

9. Nom et adresse de l'organisme exécutant
Fleet Technology Limited
16, 6325 11th Street S.E.
Calgary (Alberta)
T2H 2L6

10. N° de dossier — ASC
XSD89-00185-(631) / A

11. N° de contrat — ASC ou Transports Canada
—

12. Nom et adresse de l'organisme parrain
Centre de développement des transports (CDT)
Complexe Guy-Favreau
200 ouest, boul. René-Lévesque
Tour ouest, suite 601
Montréal (Québec) H2Z 1X4

13. Genre de publication et période visée
Finale
(mars à novembre 1990)

14. Agent de projet
P. Sémery

15. Remarques additionnelles (Programmes de financement, titres de publications connexes, etc.)

Subventionné en partie par la Garde côtière canadienne.

16. Résumé

Le logiciel désigné Shaft Modeling Tool Kit 1.0 a été le premier dans son genre à permettre d'analyser à fond le système propulsif (arbres et hélices) d'un navire devant naviguer dans la glace. Depuis octobre 1988, ce logiciel a servi non seulement à approfondir la dynamique des systèmes propulsifs pour la navigation dans la glace, mais aussi à analyser le comportement vibratoire et les défauts d'alignement associés aux systèmes propulsifs pour la navigation en eau libre. La version améliorée de ce logiciel a permis l'ajout d'une fonction pour préciser l'ampleur d'une force particulière exercée à un point donné de l'arbre et la modification de la partie relative aux réglementations pour pouvoir analyser les spécifications de divers organismes réglementaires. Ces améliorations, parmi d'autres, ont permis la mise au point de l'édition 2.0 du logiciel, lequel, après codage, a été vérifié par rapport à des résultats analytiques. En outre, des graphiques montrant les variations dans le temps des forces de torsion s'exerçant sur les lignes d'arbres en navigation dans la glace ont été obtenus par la comparaison des résultats théoriques produits par le logiciel avec les résultats pratiques tirés d'essais en vraie grandeur. Les résultats apparaissent sous forme de graphiques force-temps.

L'édition 2.0 de ce logiciel offre les fonctions suivantes : traitement des données en vraie grandeur, affichage sous forme de tableau des valeurs spécifiées dans le Règlement sur la prévention de la pollution des eaux arctiques, en plus de celles des organismes suivants : Lloyd's, ABS, Bureau Veritas et NES 304 (ministère de la Défense nationale seulement), à l'égard des systèmes propulsifs (machines, ligne d'arbres et hélices) et modélisation analytique d'un type général de ligne d'arbres pour l'étude des vibrations que font naître les forces de torsion, axiales et tranversales (fouettement), ainsi que des défauts d'alignement statique.

17. Mots clés	18. Diffusion
Ligne d'arbres, hélices, modélisation.	Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

19. Classification de sécurité (de cette publication)	20. Classification de sécurité (de cette page)	21. Déclassification (date)	22. Nombre de pages	23. Prix
Non classifiée	Non classifiée	—	42	—

SUMMARY

The Shaft Modeling Tool Kit Version 1.0 was the first available comprehensive software package for the analysis of ice class vessel shafting and propeller systems. Since its first issue in October 1988, the program has been used to study not only the dynamic problems associated with ice class shaftlines, but also the vibrational and alignment problems of open water vessel shaftlines. A contract to produce significant enhancements to the program was given by the Transportation Development Centre in cooperation with the Department of National Defence DMEE 2-7 in March 1990. These enhancements focused on the following:

- Add the capability to modify the database of component specifications
- Add the capability to specify a bi-linear stiffness for each bearing
- Add the capability to specify an input force at any location along the shaftline
- Add the regulatory requirements for shafting and propellers, when applicable, for: American Bureau of Shipping (ABS), Bureau Veritas, NES 304 (Department of National Defence [DND] only), and Lloyd's Register (LR).

These modifications make the program more general and allow the user to analyse the static and dynamic characteristics of open water and ice class vessels. The suite of programs (written for IBM PC/AT compatibles) in the Shaft Modeling Tool Kit version 2.0 provide the following main functions to the user:

1. Access to key full-scale data from several ice class vessels
2. Tabular displays of LR, ABS, Bureau Veritas, NES 304 (DND only), and CASPPR Regulations for Powering, Shafting, and Propellers
3. Analytical modeling of a generalized shaftline to calculate the torsional, axial, and transverse (whirling) vibration characteristics, as well as the static alignment condition.

This report, like the software manual, provides a description of the program, the model structure, and the solution techniques employed for the new version of the program.

Recommendations for further development are also made.

SOMMAIRE

Le progiciel désigné Shaft Modeling Tool Kit 1.0 a été le premier dans son genre à permettre d'analyser à fond le système propulsif (arbres et hélices) d'un navire devant naviguer dans les glaces. Depuis octobre 1988, ce progiciel a servi non seulement à approfondir la dynamique des systèmes propulsifs pour la navigation dans les glaces, mais aussi à analyser le comportement vibratoire et les défauts d'alignement associés aux systèmes propulsifs pour la navigation en eau libre. Le Centre de développement des transports et le ministère de la Défense nationale, DMEE 2-7, ont attribué en mars 1990 un marché visant à apporter diverses améliorations à ce progiciel, et notamment les suivantes:

- l'ajout d'une fonction permettant de modifier la base de données des spécifications relatives aux composants;
- l'ajout d'une fonction pour préciser la raideur bilinéaire associée à chacun des paliers;
- l'ajout d'une fonction pour préciser l'ampleur d'une force particulière exercée à un point donné de l'arbre;
- l'ajout des dispositions applicables, le cas échéant, aux systèmes propulsifs en vertu de la réglementation des organismes suivants: American Bureau of Shipping (ABS), Bureau Veritas, NES 304 (ministère de la Défense nationale seulement) et la Lloyd's Register of Shipping (LR).

En plus de rendre le logiciel plus universel, ces changements permettent à l'utilisateur d'analyser les caractéristiques statiques et dynamiques des navires appelés à naviguer soit en eau libre, soit dans les glaces. Le progiciel Shaft Modeling Tool Kit 2.0, qui fonctionne sur ordinateurs IBM PC/AT et compatibles, offre les grandes fonctions suivantes:

1. Traitement des données en vraie grandeur concernant des navires de différentes cotes arctiques.
2. Affichage sous forme de tableau des valeurs spécifiées dans le Réglement sur la prévention de la pollution des eaux arctiques, en plus de celles des organismes cités plus haut, à l'égard des systèmes propulsifs (machines, ligne d'arbres et hélices).
3. Modélisation analytique d'un type général de ligne d'arbres pour l'étude des vibrations que font naître les forces de torsion, axiales et transversales (fouettement), ainsi que des défauts d'alignement statiques.

À l'instar du manuel descriptif, le présent rapport décrit la nouvelle édition du progiciel en question, son architecture ainsi que les techniques qu'il met en oeuvre pour proposer des solution.

Il formule en outre des recommandations concernant la poursuite de la recherche.

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1. INTRODUCTION

During the past fifteen years Canada has achieved a position of world leadership in many aspects of the technology of Arctic marine transportation. This has come about both through the efforts of private industry and through the systematic technical programs of Government of Canada agencies such as the Canadian Coast Guard and the Transportation Development Centre of Transport Canada. The private companies involved have been concerned primarily with the technical and economic problems posed by the transportation and operational requirements of Arctic resource development. Government agencies have been primarily concerned with providing the regulatory framework for industrial operations in the Arctic and with the problems of operating and maintaining a growing fleet of ice capable shipping employed in carrying out Government missions.

A prominent feature of the Canadian approach in this field has been the emphasis upon the acquisition of full-scale engineering data and the use of operational experience to guide and inform the technology development process. This is natural considering that, in Canada, our environment presents a particularly wide range of sea ice conditions and we have had the opportunity to operate a wide range of differing ship sizes and designs in these conditions. Since the early seventies Canadian agencies and companies have either conducted or participated in more than forty major programs of full-scale experimentation with ice going ships.

As a result of this work the Shaft Modeling Tool Kit (SMTK) was developed. This software package was designed to allow the user to access the full-scale data, display the Canadian Arctic Shipping Pollution Prevention Regulations (CASPPR) for powering, shafting, and propellers, and to conduct analytical modeling on generalized shaftlines. Since its first issue in October of 1988, the program has been used not only to study ice class shaftlines, but also to analyse open water shaftline vibration and alignment conditions. Realizing the potential of the program for other uses, a project was carried out to enhance the SMTK software package to allow the user to more thoroughly analyse open water shaftlines of interest, particularly to the Department of National Defence. Version 2.0 of the SMTK has been completed, and incorporates these enhancements. This report describes the structure of the new version of the program and describes its capabilities. The model structure and the solution techniques used are also presented.

2.0 PROGRAM DESCRIPTION AND CAPABILITIES

2.1 Hardware Requirements

The following are the minimum hardware requirements:

1. IBM PC/AT Compatible Computer c/w 640 kBytes of RAM
2. EGA or VGA Graphics Card
3. EGA or VGA Colour Monitor
4. 1.2 MByte Floppy Disk Drive
5. 40 MByte Hard Disk Drive
6. Microsoft or equivalent Mouse
7. IBM Dot Matrix Printer, HP IIP Laser Printer, or equivalent
8. 80287 or 80387 math co-processor

2.2 Program Organization

Figure 2.2.1 illustrates the overall program structure flow chart. The following sections describe the program organization of each section.

Database

Figure 2.2.2 illustrates the structure of the database section of the program. The database section of the program provides quick access to data pertaining to several ice-class vessels, including component specifications and data from full-scale propulsion system monitoring. The full-scale data included was selected after an extensive review of the many documents produced and data collected from tests conducted between 1977 and 1987. The data selected represents typical and extreme events for each vessel, including ice-propeller interaction such as milling, blockage in the case of nozzled propellers, and short duration impacts. Data is presented in tables and time history plots. The user of the program can view the specifications of vessel components; display a synopsis of the full-scale tests including the environmental conditions and test specifics; and view the time history of any signal collected during one of the tests. The database help menu explains how to access and plot the full-scale data.

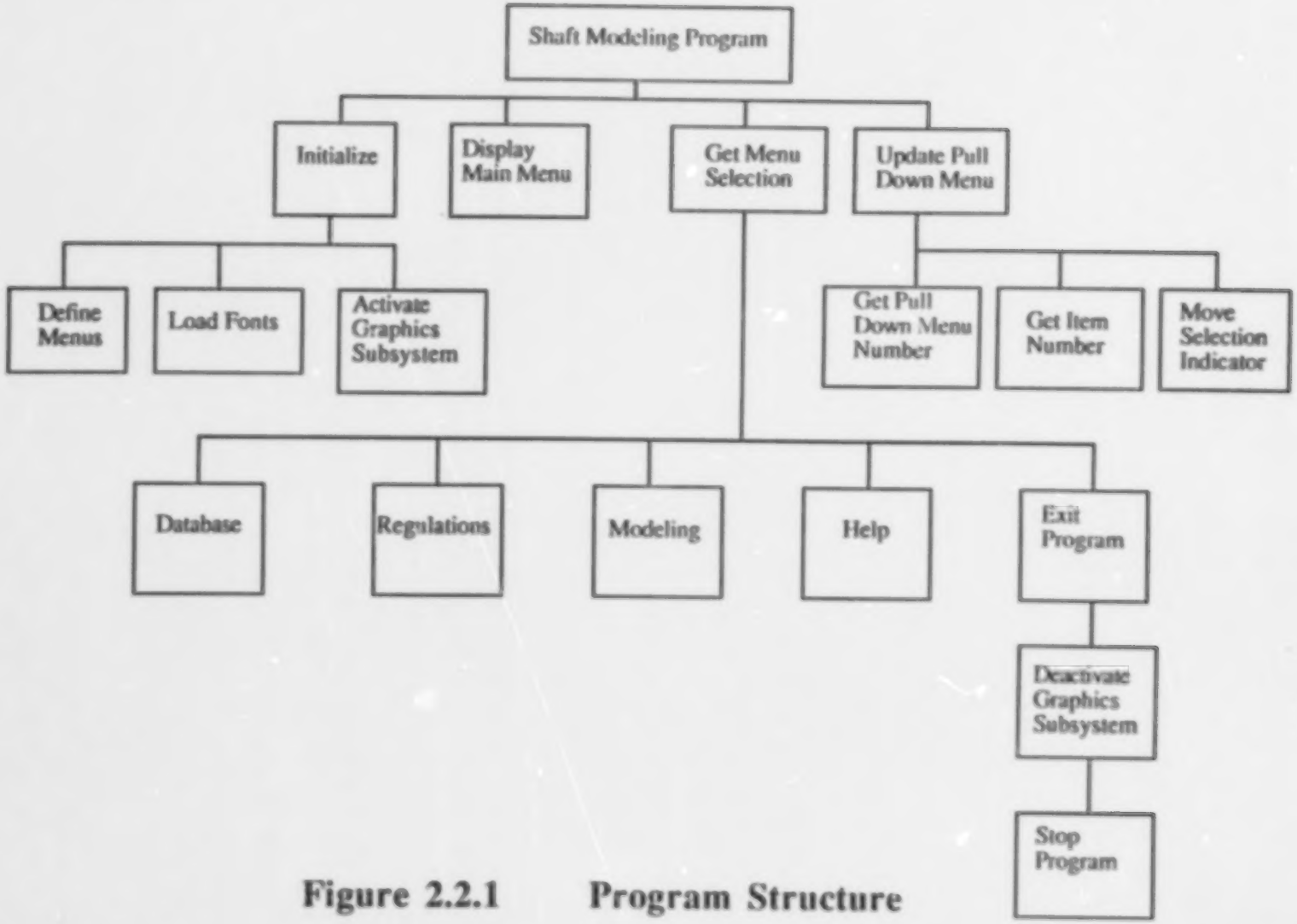


Figure 2.2.1 Program Structure

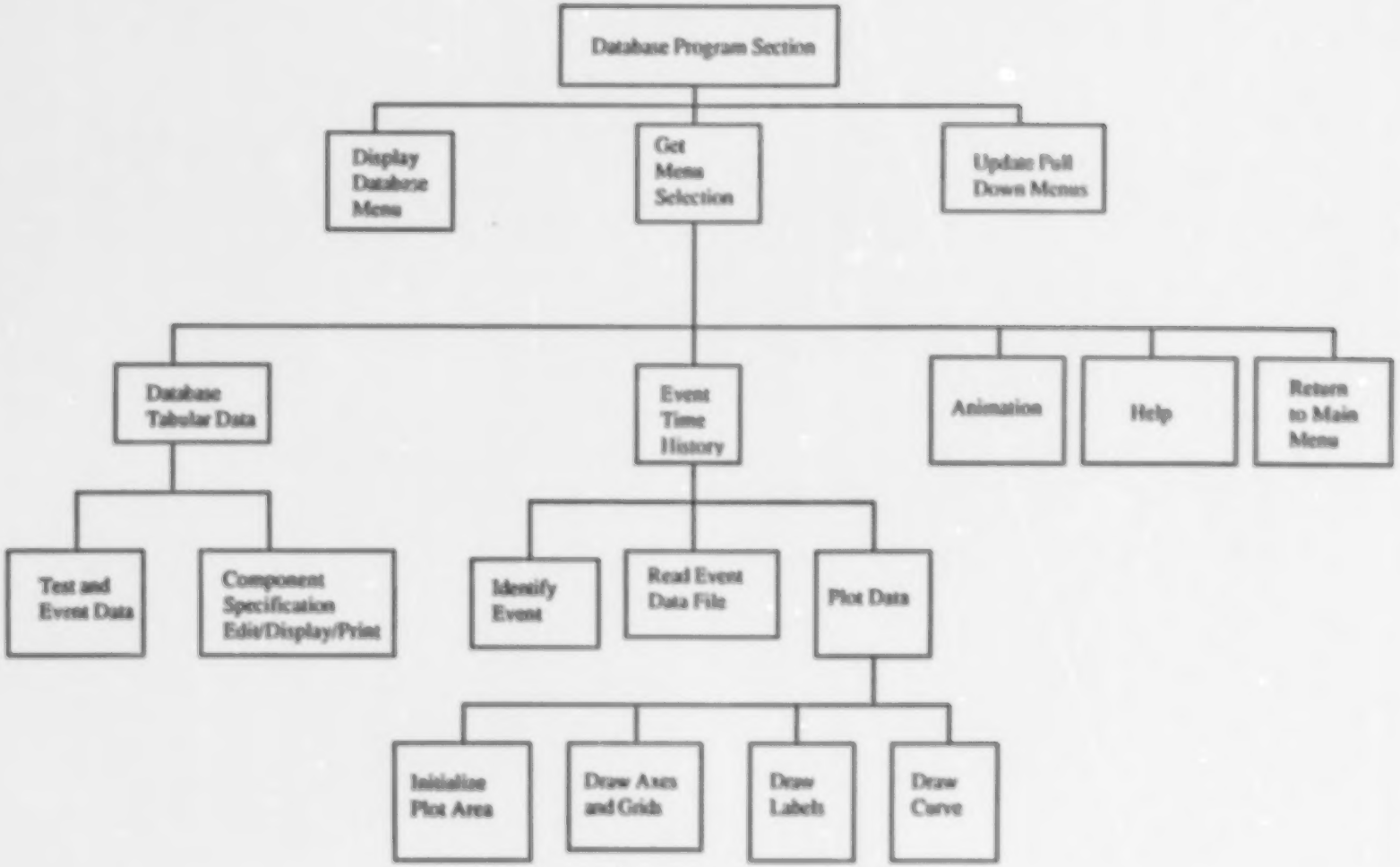


Figure 2.2.2 Structure of the Database Section

Modeling

Figure 2.2.3 illustrates the structure of the modeling section of the program. Table 2.2.1 and 2.2.2 list the model input and output parametres, respectively. The modeling section of the program provides the user with a tool to predict the dynamic response of an arbitrary shafting system due to ice-propeller interaction. Analysis options are available to calculate Torsional (Torque Model), Axial (Thrust Model), and Lateral (Alignment Model) dynamic response. A static alignment analysis option is also provided. Components such as the propeller, shafting, and concentrated inertias/masses (flywheel, gear wheel, etc) can be changed and specified by the user. Forces on the propeller used in the calculations can be specified or calculated using state of the the art ice-propeller interaction algorithms. All propeller input parametres must be specified in order that the ice-propeller interaction algorithms function properly. Forces on any shaft element can also be specified. The modeling help menu describes how to use all of the modeling features of the program.

Regulations

The regulations section of the program provides the user with a description of the current CASPPR regulations pertaining to the powering and machinery requirements. In addition the ABS, Bureau Veritas, Lloyd's, and NES 304 regulations can be accessed and displayed. This data is useful for comparing data in the full-scale database and modeling results with the expected loads and component specifications as described in the regulations.

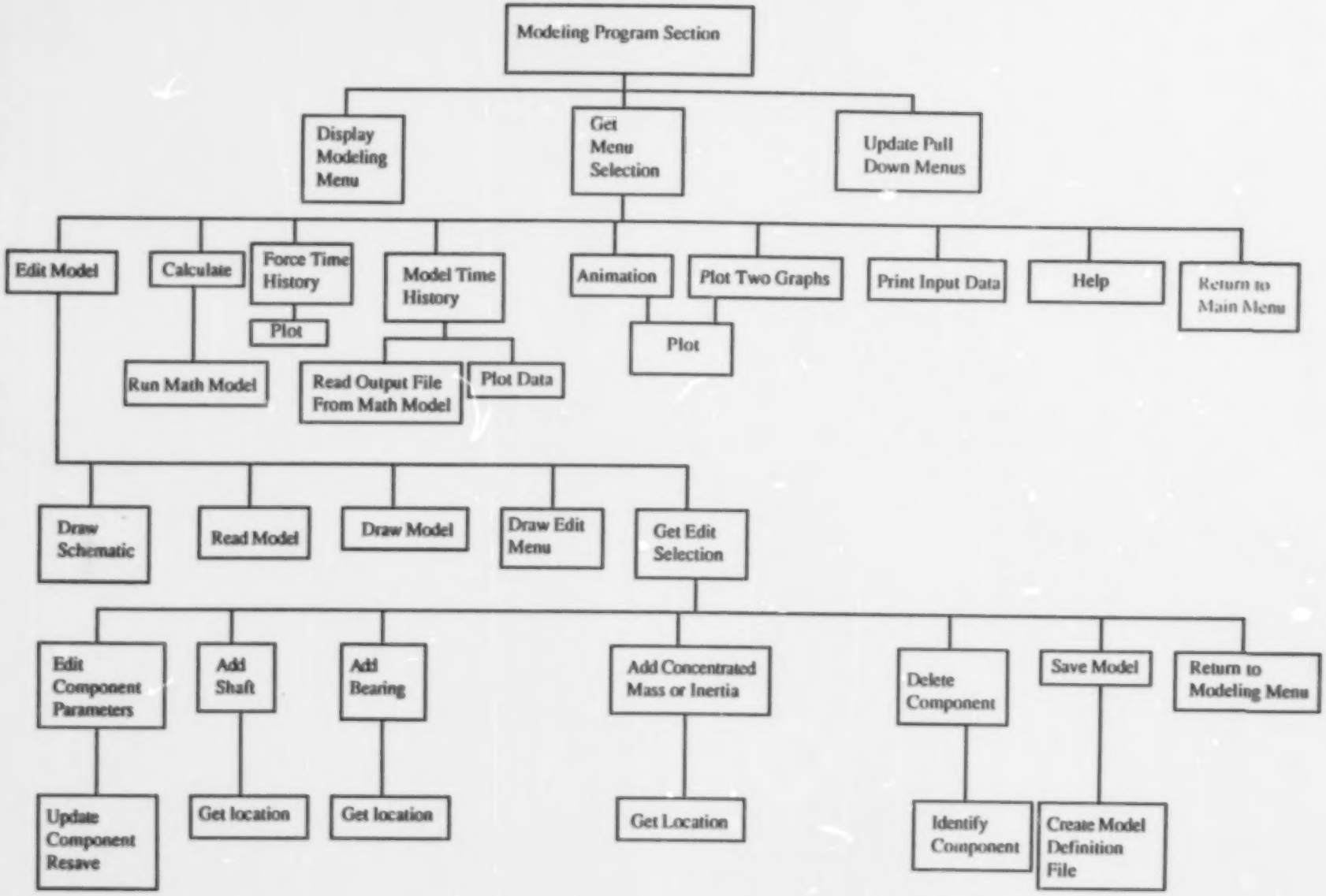


Figure 2.2.3 Structure of the Modeling Section

Table 2.2.1 Model Input Parametres

Shaft Elements	**Units**
Outside Diametre	metres
Inside Diametre	metres
Length	metres
Modulus of Elasticity (E)	GPa.
Torsional Modulus	GPa.
Mass Density	kg/m3

Propeller	**Units**
Type	1: Nozzled, 2: Open
Diametre	metres
Hub Diametre	metres
Expanded Area Ratio	/
RPM	/
Blade Width	metres
Blade Tip Thickness	mm
Blade Pitch	degrees
Polar Moment of Inertia	kgm^2
Mass	kg
Damping	Torsion: kgm^2/sec Thrust: kg/sec Alignment: kg/sec
Number of Blades	/
Blade Root Thickness	mm
CASPPR Class	/

Bearings	**Units**
Type	1: Thrust, 2: Vertical 3: Torsion, 4: Bending
Stiffness	Torsion, Bending Nm/rad Thrust, Vertical : N/m
Offset (Only Static Alignment Analysis, Vertical Bearing)	mm
Clearance (Displacement of shaft at which the stiffness is in effect)	mm
Bi-Linear Offset (Displacement of shaft at which Bi-linear stiffness is in effect)	mm
Bi-Linear Stiffness	N/m or Nm/rad (as above)

Concentrated Masses and Inertias	**Units** (for all Types)
Electric Motors, Gear Wheel, Flywheel Couplings, Oil Distribution Boxes	Torsional Inertia: kgm^2 Mass: kg

Table 2.2.1 Model Input Parametres (Con't)

Integration Parametres	Units
Time	seconds
Time Step	seconds
Damping Coefficient Alpha	/
Damping Coefficient Beta	/

Table 2.2.2 Model Output Parametres

Output Parametre	Model
Torque at each beam element	Torque Model
Thrust at each beam element	Thrust Model
Reaction of each bearing	All Models
Displacement at each node	All Model
Propeller Force Time History	All Models
Shaftline Force Time History	All Models

2.3 Database Functions

Database Time Histories

In the database section of the program, the 'Vessels' pull-down menu lists the ships for which full-scale data is present in the database. The 'Events' pull-down menu indicates the test conditions under which the data was collected; and the 'Signals' pull-down menu indicates which sensors were monitored during a particular test. The 'Events' menu changes depending on which vessel has been selected in the 'Vessels' menu. Similarly, the 'Signals' menu is dependent on the 'Events' menu and changes accordingly.

To produce a time history display of full-scale data from the database, the user must identify the data by:

1. Selecting the appropriate vessel from the 'Vessels' menu.
2. Selecting the event from the 'Events' menu
3. Selecting the signal from the 'Signals' menu.
4. Selecting 'Time History' from the 'Actions' menu.

The display produced is a 2 axis plot with the x axis in time (seconds) and the y axis in engineering units (ie. kN, mm, kNm).

Refer to the help section' Plotting Options' for information on changing the x and y scales and on producing a hard copy of the plot.

Bearing Reactions

Full-scale bearing reaction data collected during trials conducted on the M.V. Kalvik may be animated. To view the animation:

1. Select 'M.V.Kalvik" from the 'Vessels' Menu.
2. Select an event from the 'Events' menu.
3. Select 'Bearing Reactions' from the 'Actions' menu.

A display is produced with a scaled plotting area superimposed over a model diagram of the ship's propulsion system. During animation, a vertical bar is drawn at the location of each bearing along the shafts indicating the reaction at each time step. An option menu is enabled which allows the user to increase or decrease the speed of the animation; step through the animation by the indicated time step; produce a hard copy of the current display; and to abort the animation prematurely.

NOTE: This function is available for M.V. Kalvik data only.

Database Tabular Data

The database includes vessel specifications and particulars of the tests during which the waveform data was collected. This information can be displayed or printed in tabular format. The information that is displayed depends on the table type selected from the 'Actions' menu, and from the 'Vessels' and 'Components' pop-up menus.

Test and Event Data

Summaries of ice and environmental data and statistical data (maximum, minimum and mean values) for selected full-scale waveforms can be produced by:

1. Selecting the appropriate vessel from the 'Vessels' menu.
2. Selecting 'Statistics' (for statistical data) or 'Ice Conditions' (for environmental data) from the 'Actions' menu.

Vessel Specifications

Particulars of each vessel's hull, propeller, shafting, gears and bearing can be displayed by:

1. Selecting 'Vessel Specifications' from the 'Actions' menu.
2. Selecting the appropriate vessel from the 'Vessels' menu.
3. Selecting the appropriate component from the 'Components' menu.

Stored Vessel Tables

Tables can be produced, edited and stored. If 'Stored Vessels' is selected from the 'Vessels' menu, a scroll box will appear indicating the available selections. Any table can be edited and then given a new name for storage purposes. If a blank table is desired to begin with, the last entry in the scroll box 'NEW VESSEL' should be selected.

Table Editing

To edit a value contained within a 'Vessel 3pecifications' table, move the mouse to the desired item and click on it. A prompt will appear that indicates the maximum number of characters for input, and the existing value will be displayed. If no change is desired, press enter. If a change is desired, edit the exiting value and the press enter. A blank line is appended to the table for edit purposes. If this line is edited, another blank line will then be appended. A total of 32 lines are available. To insert or delete a line: click on the desired action box, move the mouse to the desired position and then click again. The scroll up and down features are only active if a table contains more than 16 lines.

Saving a 'Vessel Specification' Table

If 'Save' is selected from the edit mode, the user can then specify a file name for recall from the 'Stored Vessels' scroll box. This name is associated with each of the 5 component tables. Please not that the default vessels named in the 'Vessels' menu can not be saved by a user. If a user attempts to save a default vessel table, a new name must be input. If an existing table was selected from the 'Store Vessels' scroll box, the original name becomes the default name for storage purposes. The user can select 'Save as Named' - to update the original table, or can select 'New Name' - to create a new table.

Hard Copies

To get a printout of a table, follow the above instructions and select 'Print Table' before exiting the display mode.

Plot Two Graphs

This item can be selected from either the modeling or database 'Actions' menu. It is used to compare two time histories from any of the available waveforms, either from the full-scale database or from the modeling analysis results. The feature is useful for comparing the calculated results from a model with corresponding full-scale data, by displaying them simultaneously.

Selection of waveforms to plot is made through a series of pop-up menus. The user chooses first between 'Database' and 'Modeling' to indicate the origin of the data. If 'Database' is selected, subsequent menus ask the user to select a vessel, an event and a signal; if 'Modeling' is selected, subsequent menus ask the user to select a response type and a position (ie. node, shaft or bearing number). The user can select 'Cancel' at any menu to back up to the previous one. The process is repeated for the second waveform.

Once the waveforms are drawn, the same editing options are available as for a single waveform display as described under 'Plotting Options' in the Help menu. To enable the scaling options for one of the waveforms, it is necessary to select one waveform by clicking on the box labeled 'Switch'.

2.4 Modeling Functions

Edit Model

To make use of the Finite Element Modeling routines, the user must create and/or edit a model of a propulsion system. Model definitions are stored in files on the hard disk and may be recalled at any time. Several models are pre-defined representing a number of vessels.

To edit a model definition, the user does the following:

1. Selects the model from the' Models' pull-down menu.

2. Selects 'Edit Model' from the 'Actions' menu

The 'Models' menu lists the pre-defined models and two further options: 'New Model' and 'Stored Model'. The former permits the user to create a definition beginning with a basic model; the latter permits the user to recall a model which he has created earlier. If 'Stored Model' is enabled, a prompt box appears when 'Edit Model' is selected asking the user to input the name of the model he wishes to edit.

Editing a Model

After 'Edit Model' has been selected from the 'Actions' menu, the model diagram is displayed with a schematic drawing of the vessel propulsion system, where available, and an editing menu. Selecting the appropriate item from the menu permits the user to add or delete a component (shaft element, bearing, concentrated inertia/mass); save any changes made to the model definition file; or quit editing without saving any changes.

Adding a Component

To add a component to the model definition, the user selects the appropriate item from the menu depending on the component type he wishes to add. He then indicates where to insert the new component by clicking the mouse on the shaft immediately to the left of the position for the new component. A box appears showing default values for the required parametres for the selected component. The user can change any of the parametre values by clicking on the value to change and entering the new value from the keyboard. After making any required changes, the user selects 'Save Changes' and the component is added to the model definition. The model is also redrawn to include the new component.

If, after selecting one of the add component items from the menu, the user decides he does not wish to add a component, he may simply move the mouse so it is not touching a component and click the button.

Deleting a Component

To delete a component from the model definition, the user selects 'Delete Component' from the menu and then clicks the mouse on the component to delete. The component is removed from the model definition and the model is redrawn with the component removed.

If, after selecting 'Delete Component', the user decides he does not wish to delete any component, he may simply move the mouse so it is not touching a component and click the button.

Changing Parametre Values

The user can change any component parametre value of the model for sensitivity and parametric variation analyses. To edit the parametres of a particular component in the model, the user moves the mouse to the appropriate component and clicks the button. A box appears at the center of the screen indicating the parametres for the component and the current values. To change a value, select the parametre with the mouse and enter the new value at the prompt box with the keyboard. When all changes have been made, select 'Save Changes' to update the model definition, or 'Cancel' to ignore any changes made.

Edit Integration Parametres

When 'Edit Integration parametres' is selected from the 'Actions' menu, a window appears at the center of the screen containing the parametres and their current values. Select values to change with the mouse and enter new values from the keyboard when the prompt box appears. Select 'Save Changes' to store new values or 'Cancel' to retain the initial values when the window was opened.

The Integration Parametres are:

1. Time Step (seconds):

   Time interval in which shafting response is calculated. This value should be approximately 0.05 times the inverse of the expected frequency of vibration.

   Example: Expected Frequency = 10 Hz
   Time step = (0.05)/(10) = 0.005 seconds

   Note: If the time step is not small enough to resolve the frequency desired, the resulting waveform will appear to have damping, even if zero damping is selected.

2. Total Time (seconds):

   Total time for shafting response calculation. This value should be approximately 100-300 times the time step. The calculation time is proportional to the ratio of the total time to the time step.

3. Damping Coefficients Alpha and Beta:

   From Raleigh Damping (See Section 5.2.3 Integration Technique)

Edit Propeller Forces

Selecting 'Edit Propeller Forces' from the 'Actions' menu permits the user to edit the forcing function parametres. Values to change are selected with the mouse and stored by selecting 'Save changes'. Selecting 'Cancel' causes the initial values before change to be retained.

The parametres used in the calculations depend on the Propeller Force type selected from the 'Propeller Force' menu and the Model Type selected from the 'Analysis' menu. The following tables indicate which parametres are used for each Force type/Model with a brief description of the analysis.

Type of Force	Description	Parametres
Single Impact	One triangular shaped force impulse	Start Time, Duration
Multiple Impacts	Triangular shaped force impulses	Mag., Duration, Start Time
Ramp Force	Linear increase of force to constant value	Ramp Time, Start Time
Sine Wave	Sine wave forcing function	Frequency
Polynomial	Polynomial Equation of Force [F=f(t)]	Coefficients

Analysis Type	Description	Parametre
Torsional	Torque Loading Input	Torque (kNm)
Axial	Thrust Loading Input	Thrust (kn)
Transverse	Bending moment on propeller	Propeller Bending (kNm)
	Vertical Force Input	Vertical Force (kN)

Edit Shaftline Forces

Selecting 'Edit Shaftline Forces' from the 'Actions' menu permits the user to apply forces on any node along the shaftline. The user is first prompted to select the type of force. The next option available is to select the node number at which the force will be applied. To determine which node number corresponds to what point on the shaft, edit the model and select one of the shaft elements. The node number to the left of the element is equal to the shaft element number and the node number on the right of the element is equal to one plus the shaft element number. Then the parametres for the selected force must be chosen (see Edit Propeller Forces). The program will then calculate the specified force based upon the parametres selected, including the integration time and the time step. The selected integration time and time step should not be changed after selection of the shaftline and propeller forces. The propeller force is calculated when the user selects 'Calculate Structural Response', and is based upon the propeller force parametres last selected.

Calculate Structural Response

Selection of 'Calculate Structural Response' from the 'Actions' menu initiates the modeling calculations. The following parametres are input to the modeling calculation routines:

1. The definition of the model currently selected in the 'Models' menu.
2. The propeller force type currently selected in the 'Propeller Force' menu.
3. The ice strength currently selected in the 'Ice Type' menu , if applicable.
4. The analysis type in the 'Analysis' menu.
5. The current values of the integration parametres as set by selecting 'Edit Integration Parametres' from the 'Actions' menu.
6. The current values of the propeller forces parametres as set by selecting 'Edit Programmed Forces' from the 'Actions' menu.
7. The current shaftline forces selected in the 'Edit Shaftline Forces' in the 'Actions' menu.

The modeling routines calculate the dynamic response of the model of the shafting system by the Wilson-theta direct integration method or the static bearing reactions of a model depending on the model type selected in the 'Analysis' menu. All interaction with the program is suspended.

Calculate Natural Frequencies

Selection of 'Calculate Natural Frequencies' form the 'Actions' menu initiates a routine to calculate the eigen vector solution to obtain the natural frequencies (up to 10). The following parametres are input to the calculation of the natural frequencies.

1. The model definition currently selected in the 'Models' menu.
2. The type of analysis currently selected in the 'Analysis' menu.

Plot Response Time History

Selection of this item from the 'Actions' menu presents the user with a pop-up menu from which calculated response curves of the model may be selected for time history plots. The following table indicates what response curves are available for plotting depending on the model type selected in the 'Analysis' menu:

Model Type	Type of Response	Curves to Plot
Torque and Thrust	Shaft Displacement	Response at each Node
Torque	Shaft Torque	Response of each Shaft
Thrust	Shaft Thrust	Response of each Shaft
Transverse	Bearing Reaction	Response of each Bearing

The user uses the mouse to select the type of response to plot and then the node, shaft or bearing number. These numbers may be changed by clicking on the current value and entering a new one in the prompt box. Selecting the 'Plot' box causes the time history to be drawn; selecting the 'Cancel' box removes the pop-up menu without drawing a plot.

The node, shaft and bearing numbers can be determined in the 'Edit Model' section of the program. Clicking on a shaft or bearing opens a window containing the parametre values for that component. The title of the window includes the element number. The node number on the left side of a shaft element is equal to the shaft element number; the node number on the right side of a shaft element is equal to 1 plus the shaft element number.

Plot Force Time History

This item is selected from the 'Actions' menu in order to plot a time history of the input ice force on the propeller. If the 'Alignment' model type was run, the force plotted is the vertical ice force only; the bending moment force on the propeller is not plotted. However, the shape of the bending moment waveform is the same as the vertical ice force and magnitude is equal to that input or that calculated from the propeller model. The magnitude of the bending moment is displayed when editing the propeller forces. The user will have the option to select which input force he/she wished to plot, by clicking the mouse button and pointing to the desired force.

Plot Force Animation

The animation feature of the program, selected from the 'Actions" menu, is used to analyze the distribution of the response forces throughout the model. For example, if a torsional model is run, the magnitude of the torque response of each shaft element in the model is shown in animation as a vertical bar for each point in time. Therefore, the user can observe the decrease in torsional vibration from the propeller to the forward end of the shaftline. An option menu is enabled which allows the user to increase or decrease the speed of the animation; step through the animation by the indicated time step; produce a hard copy of the current display; and to abort the animation prematurely.

Plot Displacement Animation

This animation feature of the program, selected from the 'Actions' menu, is used to analyze the deflected shape of the shaftline due to the forces applied to it. A line plot of the displacement at each node is produced for each time step. Each displacement line is erased prior to the new line being plotted.

Plot Two Graphs

This item can be selected from either the modeling or database 'Actions' menu. It is used to compare two time histories from any of the available waveforms, either from the full-scale database or from the modeling analysis results. The feature is useful for comparing the calculated results from a model with corresponding full-scale data, by displaying them simultaneously.

Selection of waveforms to plot is made through a series of pop-up menus. The user chooses first between 'Database' and Modeling' to indicate the origin of the data. If 'Database' was selected, subsequent menus ask the user to select a vessel, an event and a signal; if 'modeling' is selected, subsequent menus ask the user to select a response type and position (ie. node, shaft or bearing number). The user can select 'Cancel' at any menu to back up to the previous one. The process is repeated for the second waveform.

Once the waveforms are drawn, the same editing options are available as for a single waveform display as described under 'Plotting Options' in the help menu. To enable the scaling options for one of the waveforms, it is necessary to select one waveform by clicking on the box labeled 'Switch'.

Print Input Parametres

Select this item from the 'Actions' menu to print a hardcopy of the current inputs to the modeling routines: model name, date and time model was last modified, the model type from the 'Analysis' menu, the force type form the 'Ice Force' menu, the ice strength from the 'Ice Type' menu, and the current values of the Integration and forcing Function parametres.

Print Model Specifications

Select this item from the 'Actions' menu to print a hard copy or the values of all parametres of all components in the currently selected model. The date and time the model was last modified is also printed.

Print Model Diagram

Select this item from the 'Actions' menu to print a hard copy of the model diagram and the propulsion system schematic diagram where one is available.

2.5 Regulation Functions

The regulations section of the program allows the user to input the powering, shafting, and propeller specifications for either an existing ship or a ship in the design stage. The minimum requirements as specified in the regulations are displayed as well as the specified design parametres and the ratio of the design specifications to the rules. The following regulations are coded into the program:

1. Canadian Arctic Pollution Prevention Regulations (CASPPR)
2. American Bureau of Shipping over 30.5 m (ABS)
3. Bureau Veritas
4. NES 304 (Available only for the Canadian Defence Department)
5. Lloyd's.

To edit and display a set of regulations the type of regulation must first be selected under the 'Regulations' pull down menu. Then the vessel must be selected under the 'Vessels' pull down menu. By selecting the any of the options under the 'Actions' menu (Powering, Shafting, Propellers) a tabular display of the regulation selected corresponding to the vessel selected is displayed. To edit any part of the regulations simply point to the element in the display and click the mouse. The 'Help' selection in the 'Actions' pull down menu will assist the user in all aspects of the operation of the regulations section of the program.

3.0 DEVELOPMENT OF MODEL STRUCTURE AND SOLUTION TECHNIQUES

3.1 Structure of Shafting Model

The development of an effective model for the dynamic response of ice class shafting systems requires a knowledge of the following:

1. Full-scale data
2. Structural dynamics
3. Numerical analysis
4. Computer applications

Full-scale data provides qualitative and quantitative information on the dynamic response of real systems, such as: measured shaft torque and thrust, bearing stiffness and damping. The development of accurate and efficient structural elements requires a modern background in structural dynamics. The efficiency of a computer modeling program depends largely on the numerical techniques employed and on their effective computer implementation. With regard to programming techniques, an optimum allocation of high and low speed storage is necessary.

The developed shaft model is composed of a linear system of continuous beam elements with concentrated springs (bearings), damping (propeller damping), and masses (electric motors, flywheels, etc.). An illustration of the M.V. Kalvik shaftline along with the model representation is shown in Figure 3.1.1. This type of modeling representation of the shafting allows for parametric variation of model components in terms familiar to marine engineers. Each beam element has a node at both ends with up to six degrees of freedom per node. Concentrated springs (bearings), torsional inertias, and masses can be applied at any node in the model. Ice forces on the propeller are included by applying an input force waveform on the node representing the propeller (extreme left node).

Three types of dynamic response calculations can be done: Thrust, Torque, and Alignment. The shafting model must be composed of at least one shaft, one bearing, and a propeller, and the type and number of bearings must be chosen such that rigid body motion be inhibited.

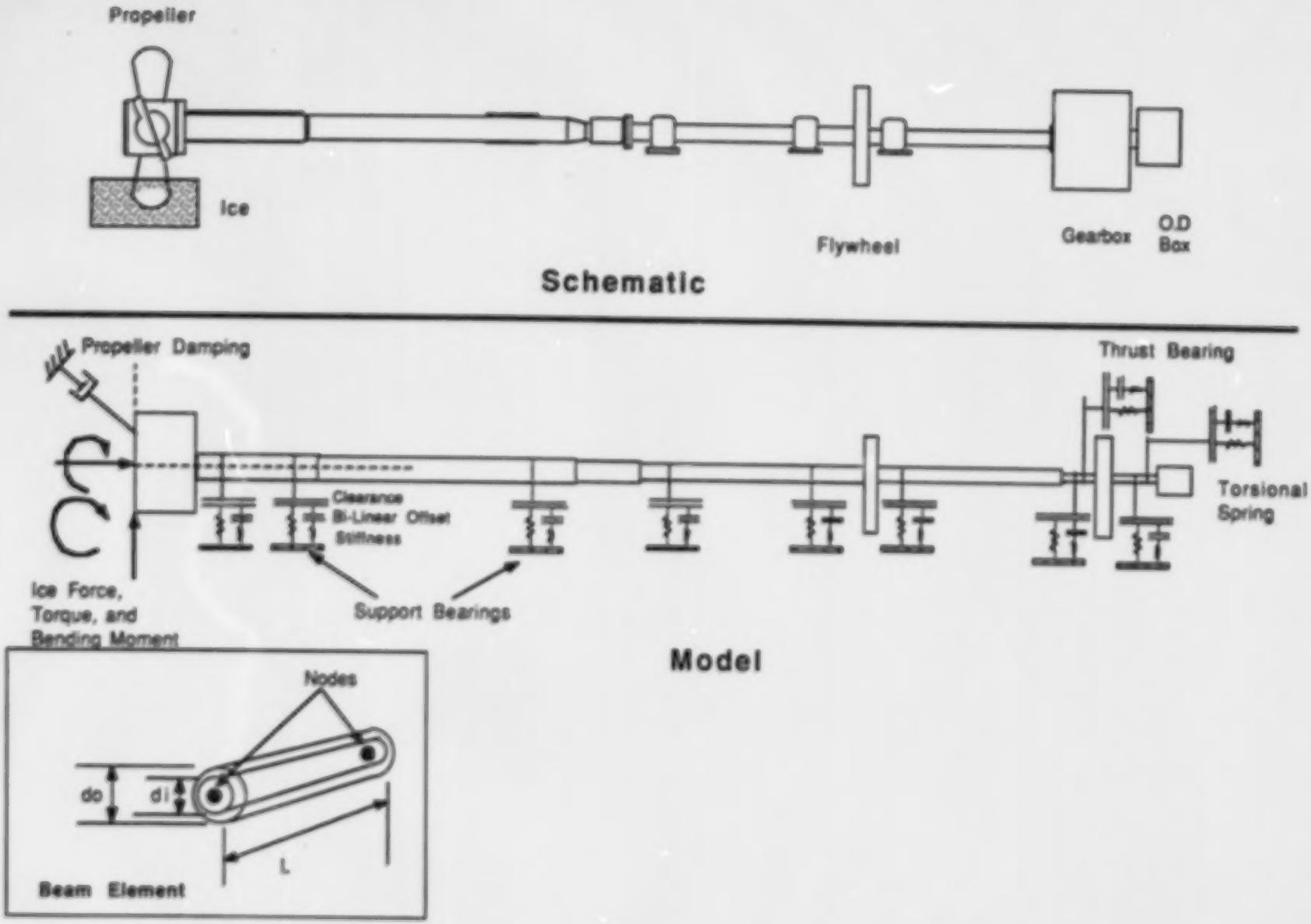


Figure 3.1.1 Modeling of the M.V. Kalvik Shaft Line

3.2 Integration Technique

The nodal point equilibrium equations for a linear system of structural elements , such as this shaft model, yield a set of linear equations of the following form:

$$[M]\{\ddot{y}\} + [C]\{\dot{y}\} + [k]\{y\} = \{F\}$$

where:

- [M] - Mass Matrix of beam element
- [C] - Damping Matrix of beam element
- [k] - Stiffness Matrix of beam element
- [F] - Forcing Function Matrix (Ice Forces on Propeller)
- $[\ddot{y}]$ - nodal acceleration matrix
- $[\dot{y}]$ - nodal velocity matrix
- [y] - nodal displacement matrix

The structural matrices (for entire model) are formed by direct addition of the element matrices: for example

$$[k] = \sum [k_m]$$

where k_m is the stiffness matrix of the m'th element. Although k_m is formally the same order as k, only those terms in k_m which pertain to the element degrees of freedom are nonzero. The addition of the element matrices can therefore be performed by using the element matrices in compact form together with identification arrays which relate element to structure degrees of freedom.

Based upon previous modeling experience and full-scale data analysis, it was determined that the modeling solution technique must conform to the following criteria:

1. Fast calculation time
2. Proven reliability
3. Ability to solve response for complex input forcing functions (ice force on propeller)
4. Capability for inclusion of lumped damping, stiffness, and mass

5. Ability to expand to more complex modeling for future development, without extensive modification to software code. Additions may include:
    - ice interaction algorithm (input force is dependent upon the response of the shaftline)
    - non-linear spring elements
6. Solve response in the form of a time history
7. Unconditionally stable

The two most common solution techniques are those of mode superposition and the direct integration method. Direct integration is equivalent to a mode superposition analysis in which all the eigenvalues and vectors have been calculated and the uncoupled equations are integrated with a common time step Δt. The integration can only be accurate for those modes for which Δt is smaller than a certain fraction of the period T (usually 0.01 times T). Using the Wilson-θ method the integration errors effectively "filter" the high mode response (ie. for which $\Delta t/T$ is large) out of the solution. This filtering is due to amplitude decay observed in the numerical solution when $\Delta t/T$ is large. The effective filtering of those high frequency response from the solution may be beneficial. Integration accuracy cannot be obtained in the response of the modes for which $\Delta t/T$ is large and the filtering process allows one to obtain a total system solution in which the low mode response is accurately observed. It is therefore noted that the direct integration technique is quite equivalent to a mode superposition analysis, in which only the lowest modes of the system, but a sufficient number to take proper account of the applied loading, are considered. The exact number of modes effectively included in the analysis depends on the time step size Δt and the distribution of the vibration periods.

The advantages of the direct integration method over the mode superposition method is that it is more effective when the response is required over relatively few time steps, such as in shock problems (propeller-ice impacts). Also the direct integration technique can accommodate non-linear spring elements and the ability to develop ice-interaction algorithms, without extensive software code revision. Therefore, the Wilson-θ method of direct integration was chosen as it satisfied all of the criteria specified.

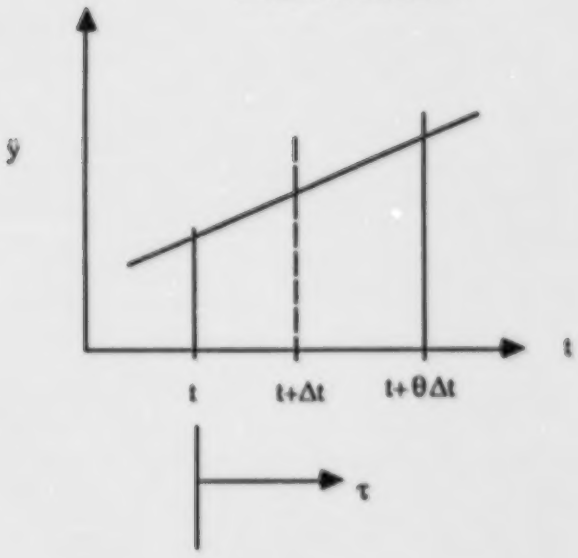
The Wilson-θ method is essentially an extension of the linear acceleration method in which the acceleration during any one time step is assumed to vary linearly. It assumes that the acceleration is linear over a range of θ times the solution time step. Paz, 1985 [1] developed the equations of motion using the Wilson-θ method by adopting an incremental load approach. The original development by Wilson was for the total load at each step, but both methods give the same final equation. The development of the equations of motions using the total load at each time step is described in the following section as well as the equations including Rayleigh damping.

Equilibrium Equations: $[M]\,[\ddot{y}] + [C]\,[\dot{y}] + [k]\,[y] = [F]$

where:

- [M] - Mass Matrix of beam element
- [C] - Damping Matrix of beam element
- [k] - Stiffness Matrix of beam element
- [F] - Forcing Function Matrix (Ice Forces on Propeller)
- $[\ddot{y}]$ - nodal acceleration matrix
- $[\dot{y}]$ - nodal velocity matrix
- [y] - nodal displacement matrix

Linear Acceleration



Solve for acceleration, velocity, and displacement, at time = t+Δt in term of values at time t.

At any time t

Acceleration:

$$\ddot{y}_{t+\tau} = \ddot{y}_t + (\tau/(\theta\Delta t))(\ddot{y}_{t+\theta\Delta t} - \ddot{y}_t) \qquad 1$$

(ie. Linear Acceleration)

Velocity:

Integrate Acceleration $\int_0^{\tau} d\tau$ to get velocity

$$\int_0^{\tau} \ddot{y}_{t+\tau}\, d\tau = \int_0^{\tau} \ddot{y}_t\, d\tau + \int_0^{\tau} (\tau/(\theta\Delta t)(\ddot{y}_{t+\theta\Delta t} - \ddot{y}_t) d\tau$$

$$\dot{y}_{t+\tau} = \dot{y}_t + (\ddot{y}_t)(\tau) + (\tau^2/(2\theta\Delta t))(\ddot{y}_{t+\theta\Delta t} - \ddot{y}_t) \qquad 2$$

Displacement:

Integrate Velocity $\int_0^{\tau} d\tau$ to get displacement

$$\int_0^{\tau} \dot{y}_{t+\tau}\, d\tau = \int_0^{\tau} \dot{y}_t\, d\tau + \int_0^{\tau} (\ddot{y}_t)\, \tau\, d\tau \int_0^{\tau} (\tau^2/(2\theta\Delta t))\, (\ddot{y}_{t+\theta\Delta t} - \ddot{y}_t)\, d\tau$$

$$y_{t+\tau} = y_t + (\dot{y}_t)(\tau) + (\ddot{y}_t)(\tau^2/(2)) + (\tau^3/(6\theta\Delta t))(\ddot{y}_{t+\theta\Delta t} - \ddot{y}_t) \qquad 3$$

Rearranging Terms:

$$\ddot{y}_{t+\theta\Delta t} = (6\theta\Delta t/(\tau^3))\, (y_{t+\tau} - y_t - (\dot{y}_t)(\tau) - (\tau^2/(2))\ddot{y}_t) + \ddot{y}_t$$

At Time $\tau = \theta\Delta t$

$$\ddot{y}_{t+\theta\Delta t} = (6/(\theta\Delta t)^2)(y_{t+\theta\Delta t} - y_t) - (6/(\theta\Delta t))y_t - 2\ddot{y}_t \qquad 4$$

At Time $\tau = \theta\Delta t$ equation **2** yields:

$$\dot{y}_{t+\theta\Delta t} = \dot{y}_t + (\ddot{y}_t)(\theta\Delta t) + (\theta\Delta t)^2/(2\theta\Delta t))(\ddot{y}_{t+\theta\Delta t} - \ddot{y}_t)$$

$$\dot{y}_{t+\theta\Delta t} = \dot{y}_t + (\ddot{y}_t)(\theta\Delta t) + (\theta\Delta t/2)[(6/(\theta\Delta t)^2)(y_{t+\theta\Delta t} - y_t) - (6/(\theta\Delta t)\dot{y}_t) - 2\ddot{y}_t - \ddot{y}_t)]$$

$$\dot{y}_{t+\theta\Delta t} = \dot{y}_t + (\ddot{y}_t)(\theta\Delta t) + (3/(\theta\Delta t))(y_{t+\theta\Delta t} - y_t) - 2\dot{y}_t - (\theta\Delta t/(2))(3\ddot{y}_t)$$

$$\dot{y}_{t+\theta\Delta t} = (3/(\theta\Delta t))(y_{t+\theta\Delta t} - y_t) - 2\dot{y}_t - (\theta\Delta t/(2))(\ddot{y}_t) \qquad 5$$

Equations of motion of an n-degree of freedom system with viscous damping and arbitrary excitation R (t+$\theta\Delta t$) can be presented in matrix form by:

$$M\ddot{y}_{t+\theta\Delta t} + C\dot{y}_{t+\theta\Delta t} + Ky_{t+\theta\Delta t} = R_{t+\theta\Delta t} \qquad 6$$

Substitute equations **4** and **5** into **6** yields:

$$M[6/(\theta\Delta t)^2(y_{t+\theta\Delta t} - y_t) - (6/(\theta\Delta t))y_t - 2\ddot{y}_t]$$

$$+ C[(3/(\theta\Delta t))(y_{t+\theta\Delta t} - y_t) - 2\dot{y}_t - (\theta\Delta t/(2)\ddot{y}_t]$$

$$+K[y_{t+\theta\Delta t}]$$

$$= R_{t+\theta\Delta t} = R_t + (\theta\Delta t)(R_{t+\Delta t} - R_t)/\Delta t$$

$$= R_t + \theta(R_{t+\Delta t} - R_t)$$

Rearranging Terms:

$$M[6/(\theta\Delta t)^2(y_{t+\theta\Delta t})] + C[(3/(\theta\Delta t))(y_{t+\theta\Delta t})] + K[y_{t+\theta\Delta t}]$$

$$= R_t + (\theta)(R_{t+\theta t} - R_t) + M[6/(\theta\Delta t)^2 y_t + (6/(\theta\Delta t)\dot{y}_t + 2y_t]$$

$$+ C[(3/(\theta\Delta t) y_t + 2\dot{y}_t + (\theta\Delta t/(2))\ddot{y}_t] \quad 7$$

OR

$$(\underline{K})(y_{t+\theta\Delta t}) = \underline{R}$$

Where:

$$\underline{K} = K + (6/(\theta\Delta t)^2)(M) + (3/(\theta\Delta t))\ C$$

$$\underline{R} = R_t + \theta\Delta R + M[(6/(\theta\Delta t)^2) y_t + (6/(\theta\Delta t\ \dot{y}_t + 2\ \ddot{y}_t]$$

$$+ C[(3/(\theta\Delta t)) y_t + 2\dot{y}_t + (\theta\Delta t/(2))\ \ddot{y}_t]$$

$\underline{K}$ = effective stiffness matrix

$\underline{R}$ = effective load vector

Substituting equation **4** into **1** for $\tau = \Delta t$

$$\ddot{y}_{t+\Delta t} = \ddot{y}_t + (\Delta t/(\theta\Delta t))[(6/(\theta\Delta t)^2)(y_{t+\theta\Delta t} - y_t) - (6/(\theta\Delta t))\dot{y}_t - 2\ \ddot{y}t - \ddot{y}_t]$$

$$\ddot{y}_{t+\Delta t} = (6/\theta(\theta\Delta t)^2)[y_{t+\theta\Delta t} - y_t] - (6/(\theta^2\Delta t))\dot{y}_t + (1 - (3/\theta))\ddot{y}_t] \quad 8$$

At $\tau = \Delta t$ equation **2** yields:

$$\dot{y}_{t+\Delta t} = \dot{y}_t + (\ddot{y}_t)(\Delta t) + (\Delta t^2/(2\theta\Delta t))(\ddot{y}_{t+\theta\Delta t} - \ddot{y}_t) \quad 9$$

Rearranging terms in equation **1** and setting $\tau = \Delta t$

$$\ddot{y}_{t+\theta\Delta t} = (\ddot{y}_{t+\Delta t})(\theta\Delta t/(\Delta t)) - (\theta\Delta t/(\Delta t))(\ddot{y}_t) + \ddot{y}_t \quad 10$$

Substituting **10** into **9** at $\tau = \Delta t$ yields:

$$\dot{y}_{t+\Delta t} = \dot{y}_t + (\ddot{y}_t)(\Delta t) + (\Delta t/(2\theta))[(\ddot{y}_{t+\Delta t})(\theta) - \theta\,\ddot{y}_t + \ddot{y}_t - \ddot{y}_t]$$

$$\dot{y}_{t+\Delta t} = \dot{y}_t + (\Delta t/2)(\ddot{y}_{t+\Delta t} + \ddot{y}_t) \qquad 11$$

Substituting equation **10** into **3** at $\tau = \Delta t$ yields:

$$y_{t+\Delta t} = y_t + (\dot{y}_t)(\Delta t) + (\ddot{y}_t)(\Delta t^2/2) + (\Delta t^3/(6\theta\Delta t))[(\ddot{y}_{t+\Delta t})(\theta) - (\theta)\,\ddot{y}_t + \ddot{y}_t - \ddot{y}_t]$$

$$y_{t+\Delta t} = y_t + (\dot{y}_t)(\Delta t) + (\Delta t^2/6)(\ddot{y}_{t+\Delta t} + 2\ddot{y}_t) \qquad 12$$

3.3 Damping

Raleigh damping: $C=\alpha[M]+\beta[K]$ where: α and β are constants

The constants α and β can be chosen to best fit the damping characteristics of system. Typically a sensitivity analysis is done to determine what changes in α and β have on the response of the shafting system.

Using Raleigh damping the modal damping ratio becomes: $\xi_i = \alpha/(2\omega_i) + \beta\omega_i/2$

where: ξ_i= modal damping ratio
ω_i= natural frequency of the i'th modal response

If α is set to zero (0) then the damping becomes structural and $\beta=2\xi_i/\omega_i$

for critical damping: $\xi_i = 1$
$\beta = 2/\omega_i$

3.4 Static Alignment

The solutions to the static vertical bearing reactions for a shaft model are solved from the static equilibrium matrix equation:

$$[F]=[k][y]$$

where:

[F] = Force matrix
[k] = Stiffness matrix
[y] = Nodal displacement matrix (displacement of each node)

The static alignment algorithm performs the following:

1. Calculates the stiffness matrix as is done in the dynamic analysis
2. Calculates the force matrix based upon:
   - the shaft weight
   - the force to move the shaft to the specified offset at each bearing
3. Solves the nodal displacement matrix for the calculated force and stiffness matrices
4. Calculates the vertical force, F_v, in each shaft element, by multiplying the calculated nodal displacement by the appropriate stiffness at each node.
5. Calculates the bearing reactions from the nodal static equilibrium conditions ($\sum F_v=0$).

The bearing influence coefficients are calculated by setting the offset of one bearing by 1 mm and setting the offset of the others to 0 mm, calculating the static alignment condition, and then repeating the procedure for each bearing. This provides the reaction change of each bearing by lowering a bearing by 1 mm (ie. the influence coefficient matrix).

4.0 Ice-Propeller Interaction Forces

Full-scale data of the shaft torque from various icebreakers was analysed using the Shaft Modeling Tool Kit (SMTK), to estimate the shape and magnitude of the ice torque on the propeller. Because of the expense and difficulty of directly measuring the propeller loads during ice interaction, the method presented here is very cost effective when analyzing a number of vessels. In addition the most advanced ice-propeller interaction analytical formulations still have a large error associated with them, and therefore the more direct approach described here is the author's recommended procedure for determining ice-propeller interaction forces. An iterative procedure was employed and this involved the following:

1. A model of the shaftline was constructed.

2. Examination of the measured shaft torque history was done to provide an estimate of the magnitude and shape of the propeller torque or thrust that caused a particular shaftline response. Usually a similar shape to the shaft torque waveform is input with a higher dynamic amplitude.

3. The calculated shaft torque time history was then compared to the measured dynamic component of the full-scale data. Estimations of the increase in magnitude and impact duration were made based upon the relative shape and amplitude of the two waveforms.

4. Based upon the above estimate a revised propeller force was input into the shaftline model and the structural response was calculated again.

5. Steps 3 and 4 were repeated until a satisfactory match between the calculated and measured shaft torque waveforms was obtained. The resulting propeller force would then be an estimate of the actual force that caused the measured shaft torque.

Figures 4.1 to 4.6 present the results of this analysis.

Modelling Input Parameters

Name of Model:	T11_FTL
Date:	11/18/90
Time:	14:23:50
Analysis Type:	TORSIONAL VIBRATION

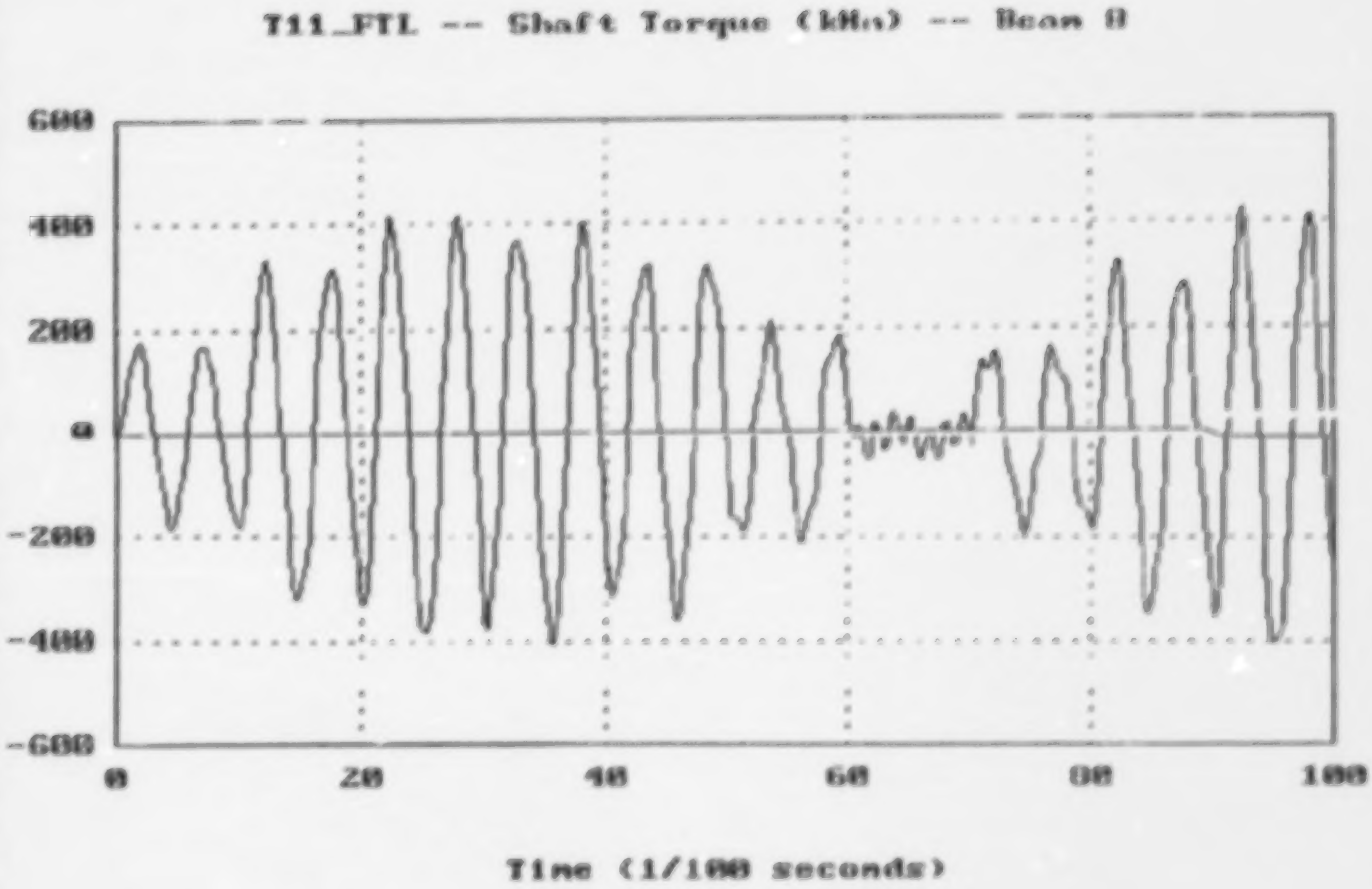


Figure 4.1 Calculated Shaft Torque of Type 1100 Coast Guard Vessel

Modelling Input Parameters

Name of Model:	T11_FTL
Date:	11/18/90
Time:	14:23:50
Analysis Type:	TORSIONAL VIBRATION

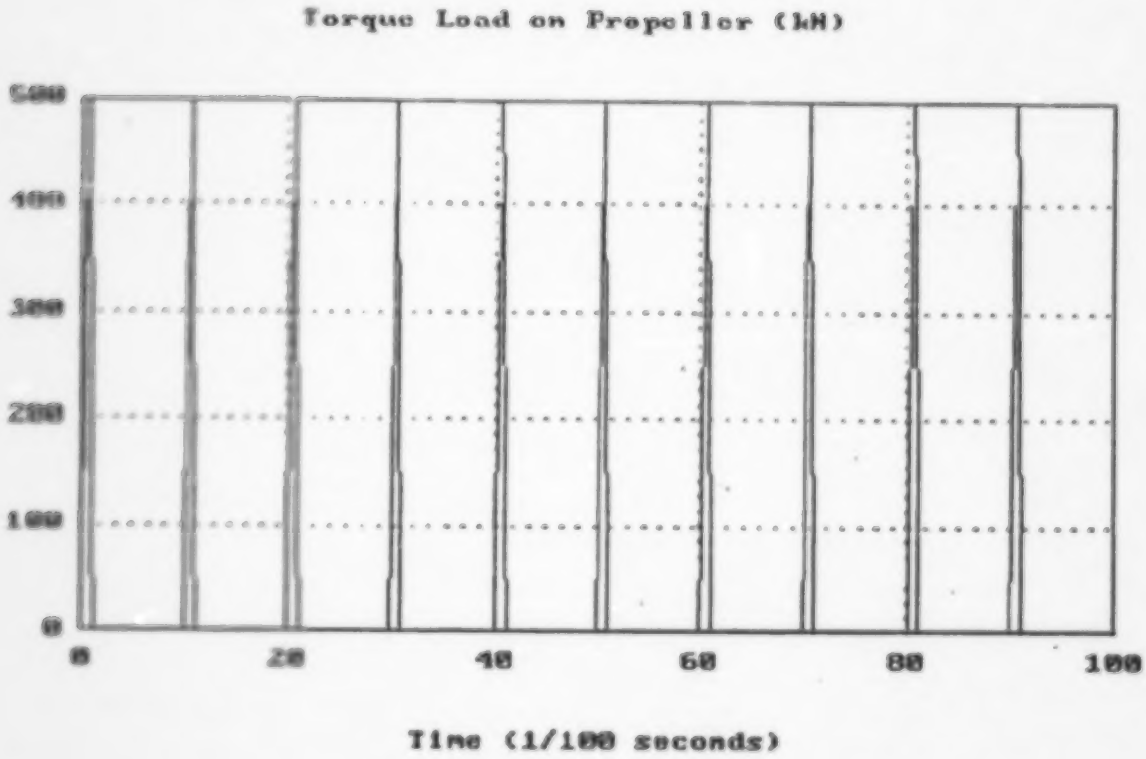


Figure 4.2 Estimated Ice Torque on Propeller of Type 1100 Coast Guard Vessel (Impact Duration = 0.01 Sec., Impact Frequency = 10 Hz (Blade Rate)

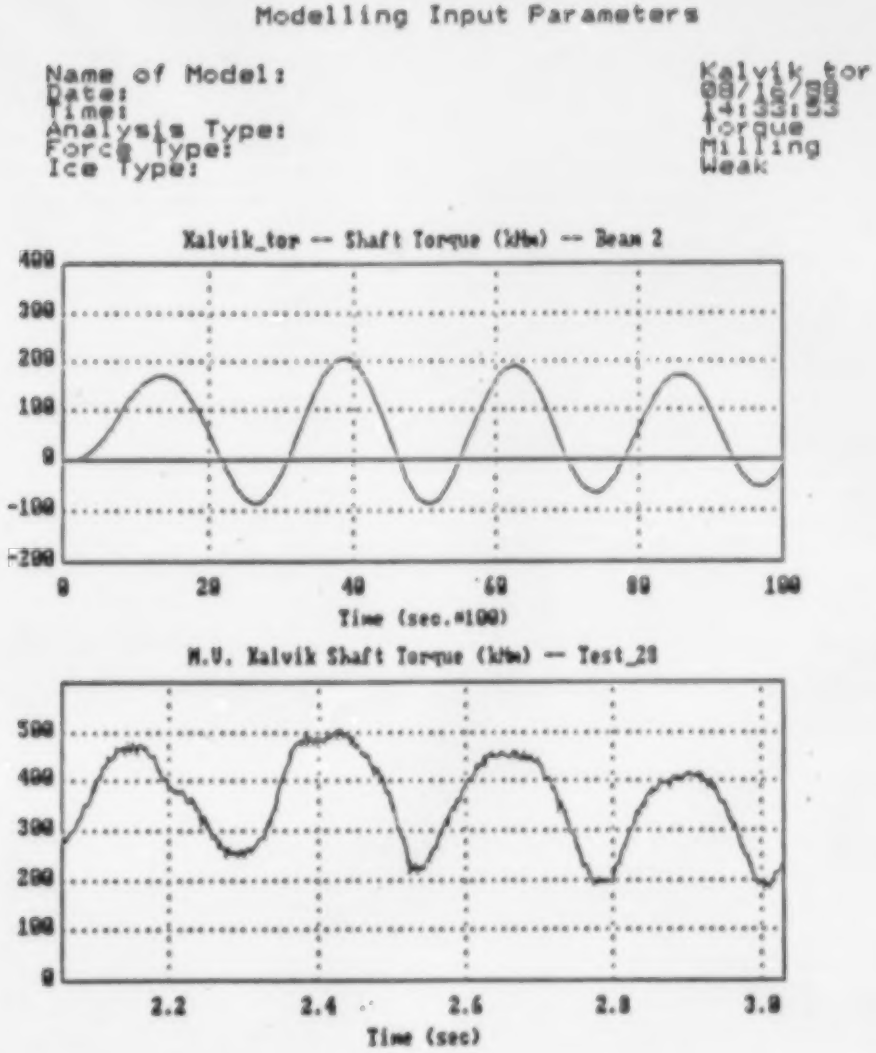


Figure 4.3 Calculated and Measured Shaft Torque: MV Kalvik

Modelling Input Parameters

Name of Model:	Kalvik tor
Date:	08/16/88
Time:	14:33:53
Analysis Type:	Torque
Force Type:	Milling
Ice Type:	Weak

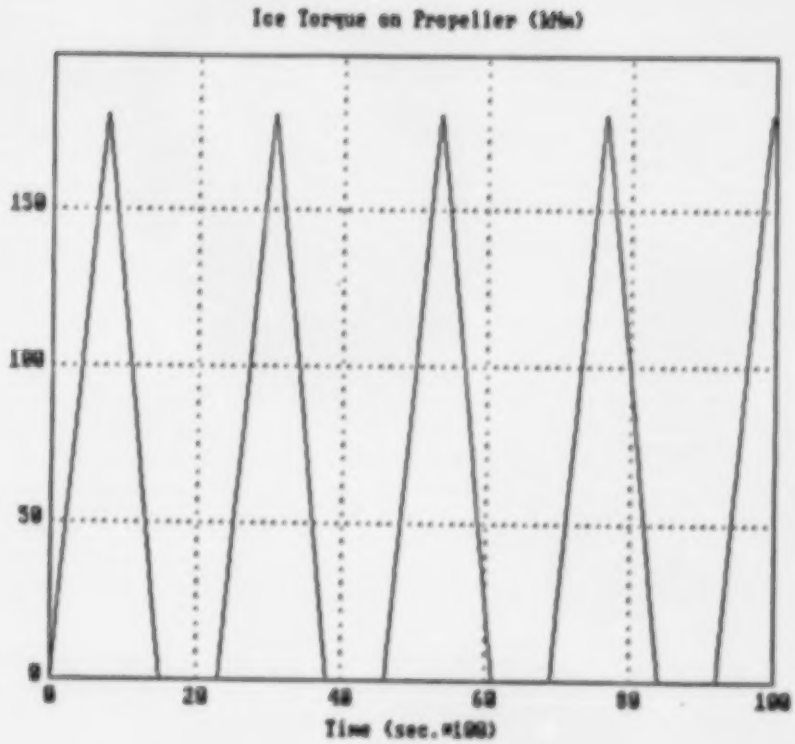


Figure 4.4 Estimated Ice Torque on Propeller of MV Kalvik
(Impact Duration = 0.15 Sec., Impact Frequency = 4.5 Hz (1/2 Blade Rate)

Modelling Input Parameters

Name of Model:	polar8_n2
Date:	08/16/88
Time:	15:21:30
Analysis Type:	Torque
Force Type:	Milling
Ice Type:	Weak

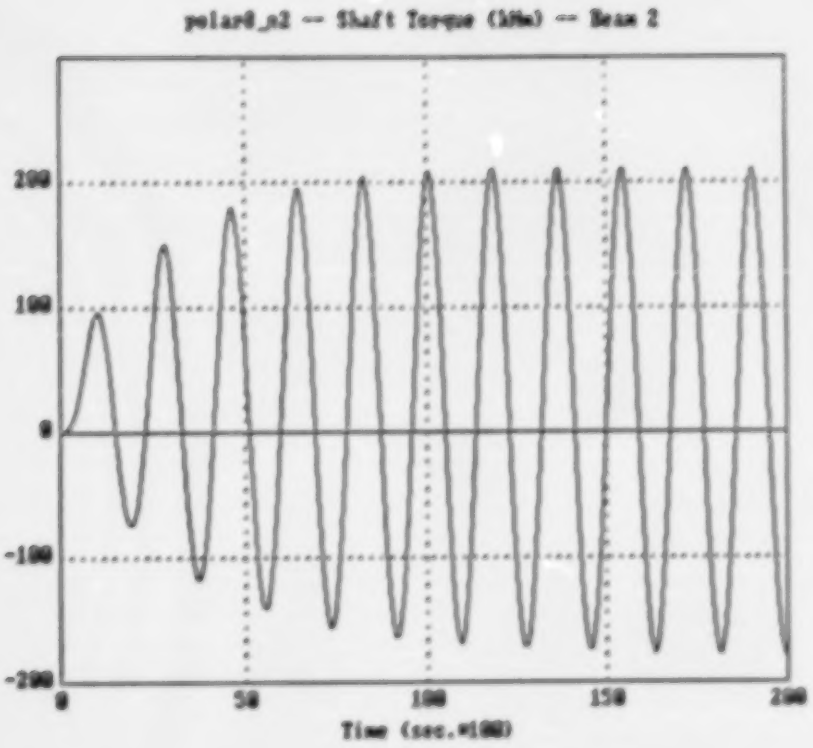


Figure 4.5 Calculated Shaft Torque for ASPPR Class 8 Shaftline: Open Screw

Modelling Input Parameters

Name of Model:	polar8_n2
Date:	08/16/88
Time:	15:21:30
Analysis Type:	Torque
Force Type:	Milling
Ice Type:	Weak

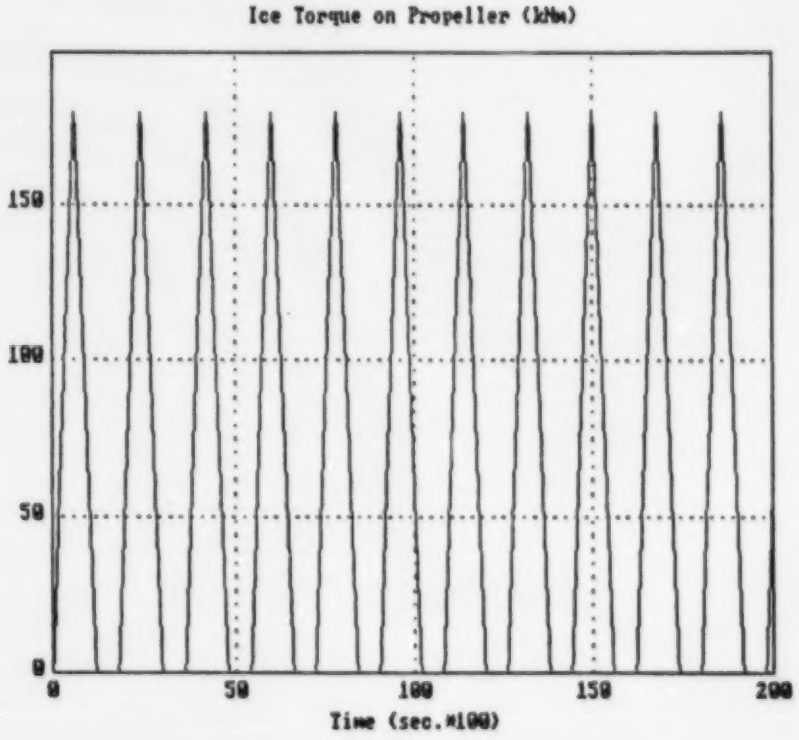


Figure 4.6 Estimated Ice Torque on Propeller of ASPPR Class 8 Shaftline: Open Screw (Impact Duration = 0.11 Sec., Impact Frequency = 6 Hz (1st Harmonic)

5.0 RECOMMENDATIONS

The following are recommendations for further development in this area:

- Obtain more full-scale data on the vibration characteristics of DND and Coast Guard Vessels. This data will greatly assist in the specification of various empirical parametres (such as propeller damping) for shaftline models.

- Develop shaftline models for a number of DND and Coast Guard vessels.

- Add to the database the specifications for a number of DND and Coast Guard vessels.

- Determine inadequacies of the regulations based upon analysis of full-scale data and execution of shaftline models.

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